

Title: Single Axis Flywheel IPACS @1300W, 0.8 N-m
Author: Ralph Jansen
Forum: Space Power Workshop, April 21st, 2005.

NASA Glenn Research Center is developing flywheels for space systems. A single axis laboratory version of an integrated power and attitude control (IPACs) system has been experimentally demonstrated. This is a significant step on the road to a flight qualified three axes IPACS system. The presentation outlines the flywheel development process at NASA GRC, the experimental hardware and approach, the IPACS control algorithm that was formulated and the results of the test program and then proposes a direction for future work. GRC has made progress on flywheel module design in terms of specific energy density and capability through a design and test program resulting in three flywheel module designs. Two of the flywheels are used in the 1D-IPACS experiment with loads and power sources to simulate a satellite power system. The system response is measured in three power modes: charge, discharge, and charge reduction while simultaneously producing a net output torque which could be used for attitude control. Finally, recommendations are made for steps that should be taken to evolve from this laboratory demonstration to a flight like system.

The presentation describes NASA Glenn Research Center's laboratory demonstration of a single axis Integrated Power and Attitude Control System (IPACS) with 2000W power and 0.8 N-m capabilities. The system utilizes two development flywheel modules, D1 and G2. The modules have carbon fiber energy storage wheels, permanent magnet motor generators, and magnetic bearings. They operate between 20,000 and 60,000 RPM and have integral vacuum chambers to reduce windage drag.

The IPAC System integrates the energy storage and attitude control functions into a single system that performs the power management and momentum control functions. Previously the GRC team had simulated and tested the two flywheel system and demonstrated IPACS at low power levels and speeds using D1 and another flywheel module. With the completion of the new G2 flywheel we have been able to demonstrate full power and full speed operation of the single axis IPACS system.

The electrical power system (EPS) operates using the same modes as the International Space Station: charge, charge-reduction, and discharge. The system enters charge mode when the power available is greater than the sum of the load and the flywheel charge rate command. Charge reduction mode occurs when the power available is greater than the load but less than the sum of the load and the flywheel charge rate command. The discharge mode condition occurs when the available power is less than the load. Voltage is regulated by the solar array in charge mode and by the flywheel system in the other modes. In charge mode the current into the flywheel system is equal to the charge command. In the other modes the current is determined by the voltage regulation algorithm with current flowing into the flywheels during charge reduction mode and from the flywheel during discharge. Power regulation was demonstrated charging at 2100W and discharging at 1300W into a resistive load. Transient effects of mode transitions from charge to discharge and load steps were also measured.

Most of the attitude control (AC) testing was done by issuing an open loop torque command and measuring the torque produced by the system. Open loop torque testing was selected to simplify the measurement of coupling between the EPS and the AC functions. A simple PID attitude control loop was added to demonstrate angular control. Limitations including cable drag and vacuum connections restricted the range of motion and accuracy of attitude control demonstrations. Steady state and transient open loop torque measurements were made. Finally transient attitude control tests were conducted.

Single Axis IPACS @1300W, 0.8 N-m

Ralph Jansen

Dr. Barbara Kenny, Peter Kascak, Tim Dever, Walter Santiago

Presented at the Space Power
Workshop

April 20th, 2005



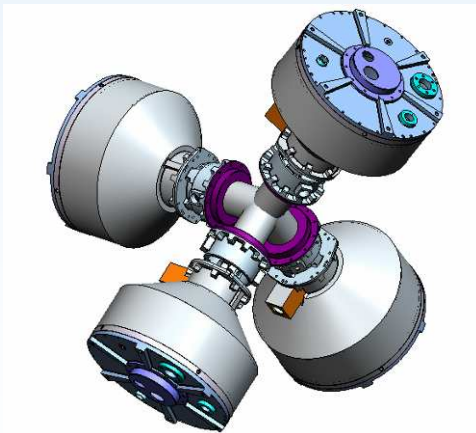
Outline of Presentation

- Flywheel IPACS options
 - Body Mounted
 - Gimbaled
- NASA GRC flywheel program background
- Current Regulation
- Bus Regulation
- Torque Control
- Initial Orbit Simulation Experiment
- Conclusions

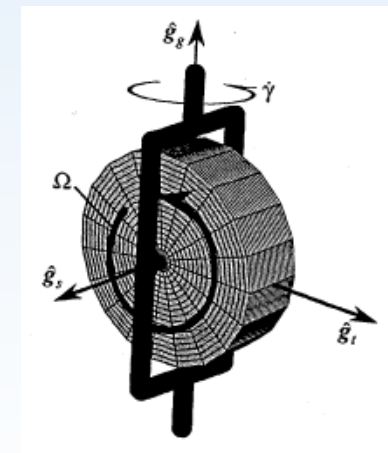


IPACS Options

- Body Mounted Reaction Wheel
 - Momentum vector of wheels are fixed w.r.t. spacecraft
 - Wheel speed is determined by simultaneously solving the bus regulation and torque equations.
- Variable Speed Control Moment Gyro.
 - Momentum vector of wheels are rotated w.r.t. spacecraft to produce torque
 - Wheel speeds are varied for bus regulation



Kascak, P.; Jansen, R.; Dever, T.; Kenny, B., "Demonstration of Attitude Control and Bus Regulation with Flywheels", Proceedings of the 39th IAS Annual Meeting; Seattle WA, Oct 2004.



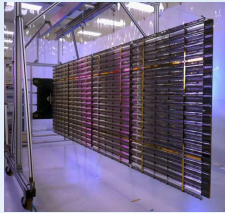
Fausz, J.; Richie, D., "Flywheel Simultaneous Attitude Control and Energy Storage Using a VSCMG Configuration", 2000

Richie, D; Tsiotras, P.; Fausz, J., "Simultaneous Attitude Control and Energy Storage using VSCMGs: Theory and Simulation", 2001.

What is a Flywheel System?

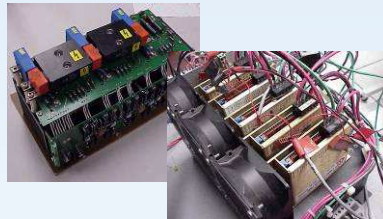
Sources

Provide Energy

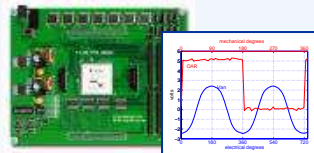


Solar Arrays

Flywheel Avionics
Transform Electrical to
Mechanical Energy



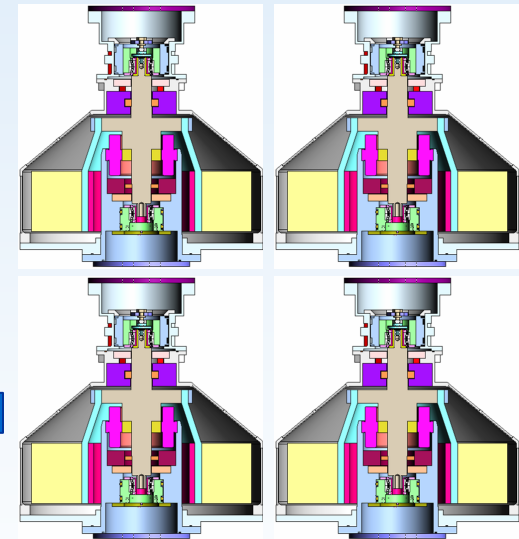
Power Electronics for
M/G and MB



Controller Hardware &
Algorithms for M/G and
MB

Flywheel Modules

Store Energy and
Momentum



Four G3 Flywheel Modules

Loads
Consume Energy



Instruments



Antennas



Ion Thrusters



Sensors

Flywheel Technology Development Approach

System Application Challenges

- *Power/Momentum Mgmt.*
- *High Specific Energy*
- *Efficiency*
- *Safety*
- *High Specific Power*
- *Deployment*
- *System Integration*



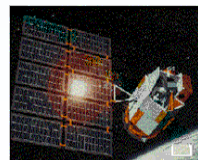
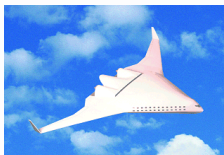
Component Technology Development Challenges

- *Rotors*
- *Magnetic Bearings*
- *Motor/Power Electronics*
- *Systems/Controls*

Integrated System Demonstrations

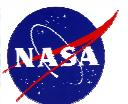
- *Power Momentum Mgmt.*
- *Energy Density*
- *Efficiency*

Flight Systems



Glenn Research Center

at Lewis Field

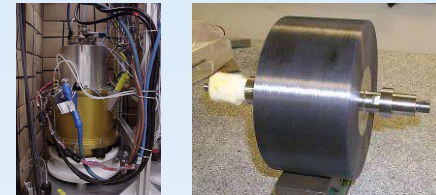


NASA Flywheel Program

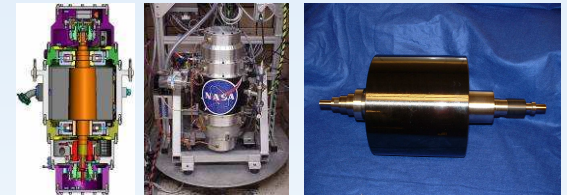
Recent Accomplishments

- **D1 flywheel upgraded and tested to 60,000 RPM**
 - Capable of repeated test operation between 20,000 and 60,000 RPM at 1000 Watts
- **NASA GRC G2 flywheel designed, fabricated and tested to 42,000 RPM**
 - Incorporated lessons learned from D1 Upgrade
 - First use of TAMU low loss magnetic bearing design
 - Operational checkout completed in record time with integrated dynamics and control models
 - Design capable of continuous operation between 20,000 and 60,000 RPM at 1000 watts
- **NASA GRC G3 advanced flywheel CDR completed**
 - Meet near term performance metrics (25 whr/kg system, 85% r/t eff., 90,000 cycles at 75% DOD)
 - High efficiency NASA motor design
 - High specific energy composite arbor rotor, UT-CEM
 - Low loss, redundant magnetic bearings, TAMU/VCEL
- **Demonstrated single axis IPACs at full power and torque for ISS type power bus**
 - Deliver up to 1000 w, each unit
 - Approximately 300 w-hr, each unit
 - Deliver up to 0.8 n-m, system
 - Operational speed range, 20,000-60,000 RPM
 - Demonstrated charge, discharge and charge reduction modes to 120V ISS Bus
 - Simultaneously deliver commanded torque output

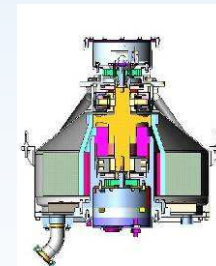
D1 Module



G2 Module



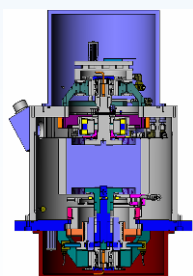
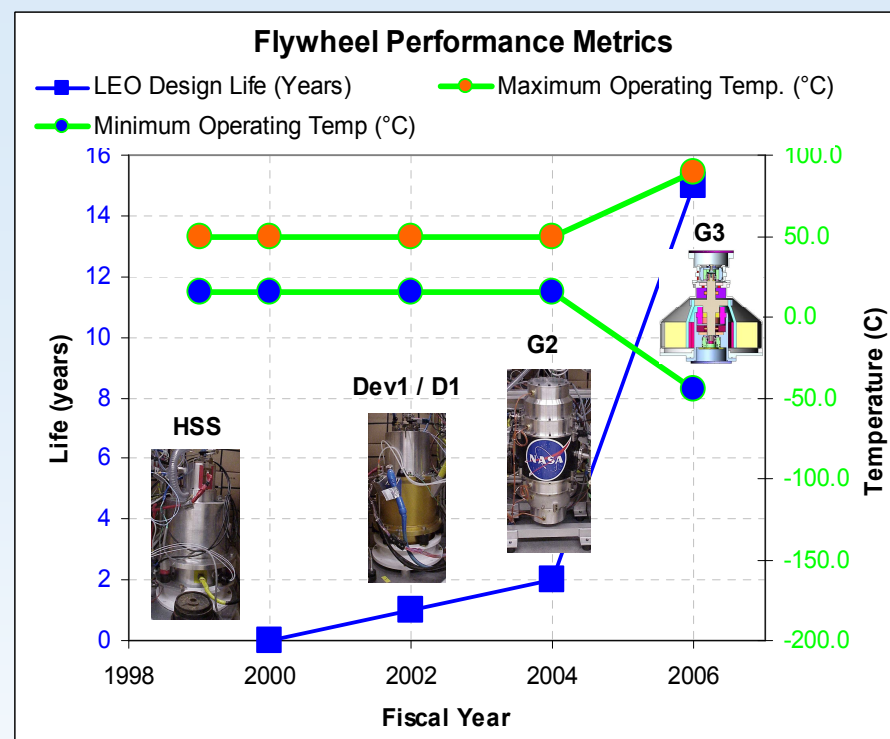
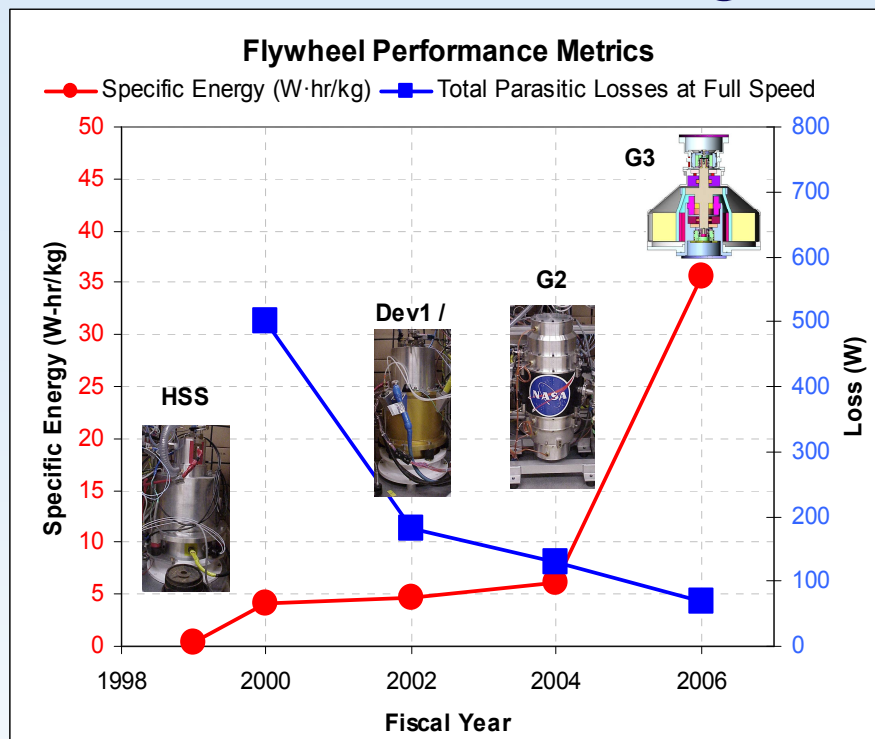
G3 Module



D1/G2 Modules
In HEFF Air-Table
Test-bed



NASA Progress on Performance

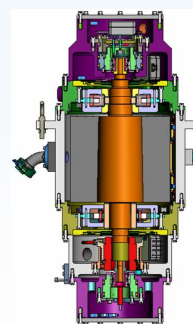
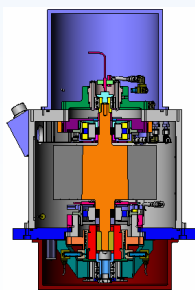


Dev 1 - 300 W-hr
4.1 W-hr/kg
Full Speed Once

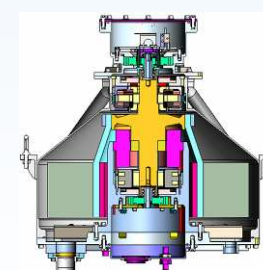
USFS



D1 - 330 W-hr
4.7 W-hr/kg
Full Speed Many Times
GRC/TAMU/USFS



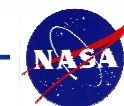
G2 - 581 W-hr
6.1 W-hr/kg
Modular, Low Cost
GRC/TAMU



G3 - 2136 W-hr
35.5 W-hr/kg
High Energy, S.E., Life
GRC/TAMU/UT-CEM

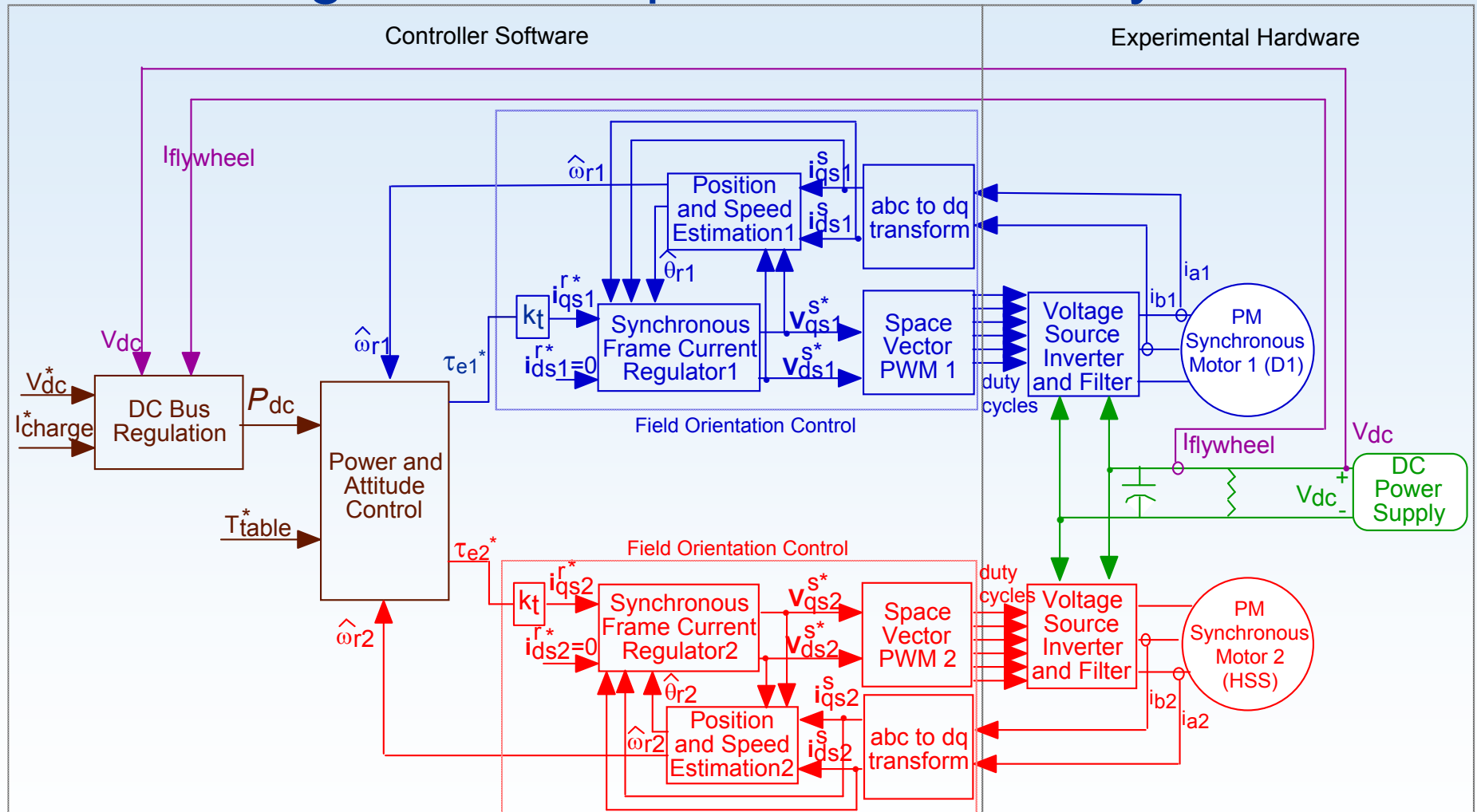
Glenn Research Center

at Lewis Field



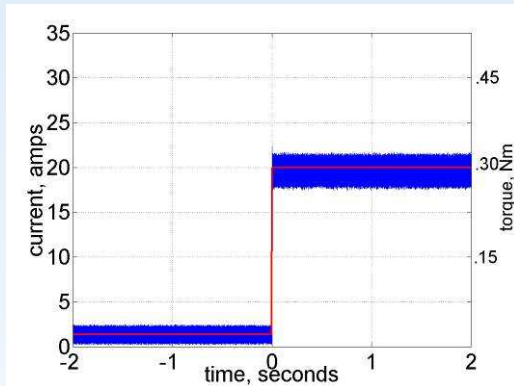
Attitude Control and Bus Regulation

- Change outer loop to control two flywheels

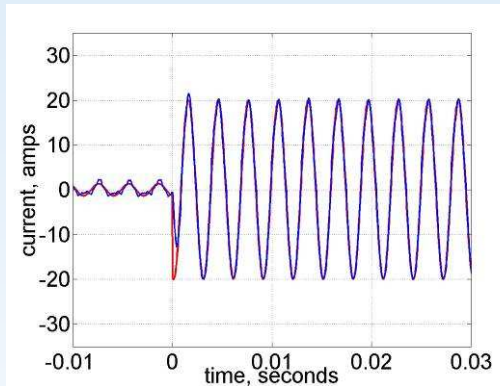


Motor Current Regulation Bandwidth

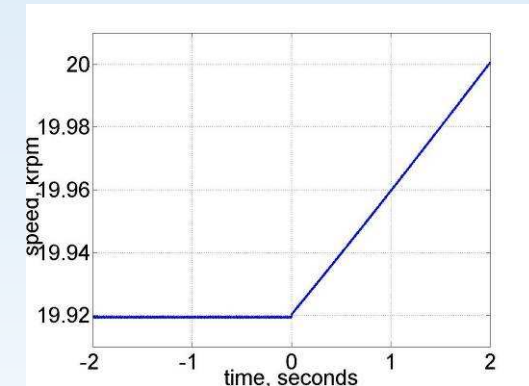
**Current
Magnitude and
Torque Response**



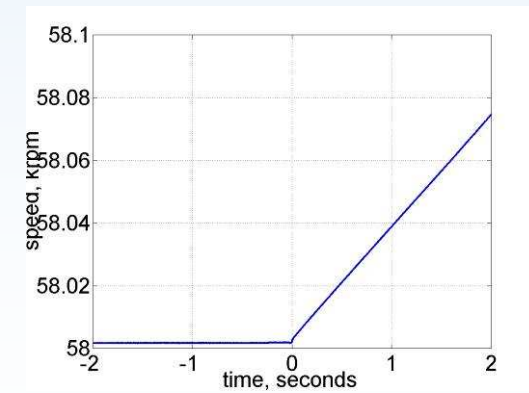
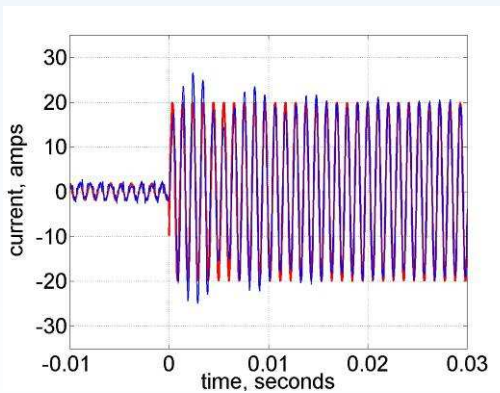
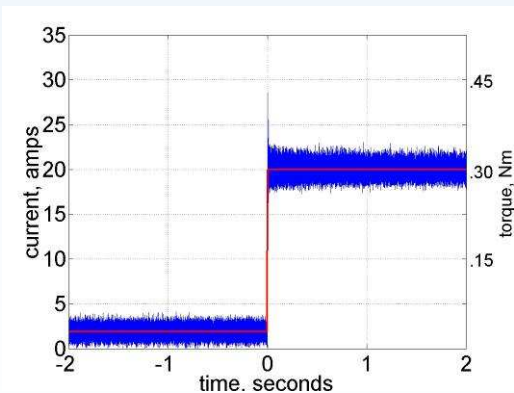
**Motor Phase
Current**



Flywheel Speed

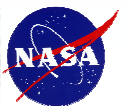


60,000 RPM



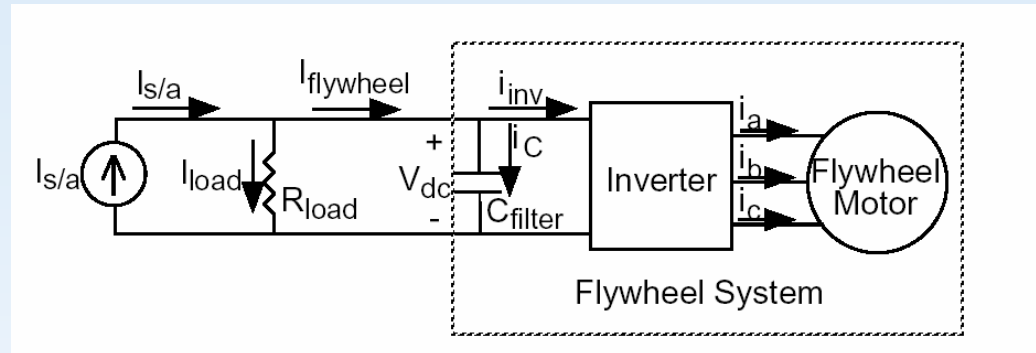
Glenn Research Center • 1 kHz bandwidth torque response




at Lewis Field



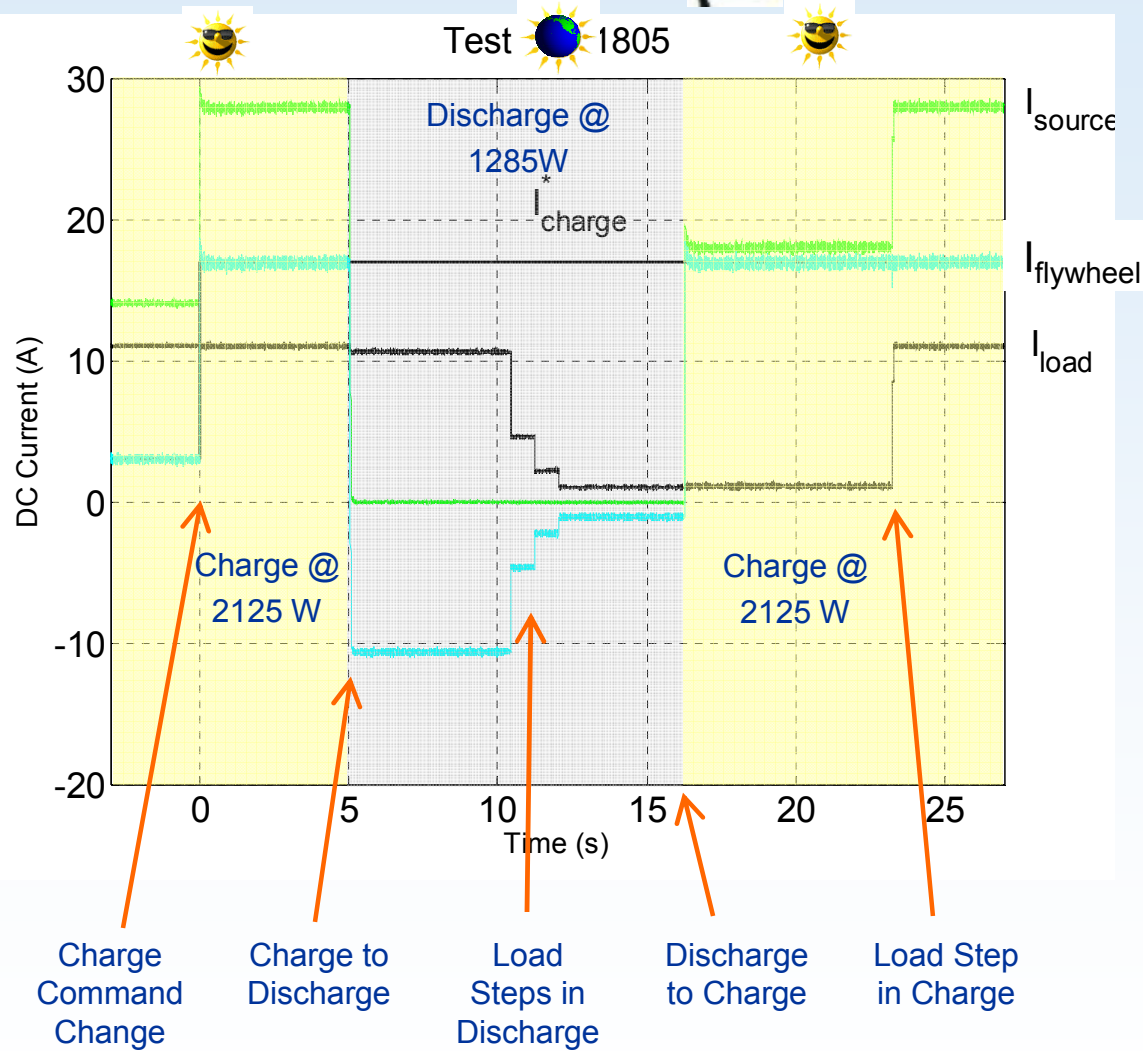
Flywheel Bus Regulation Control

- Charge
- Charge Reduction
- Discharge

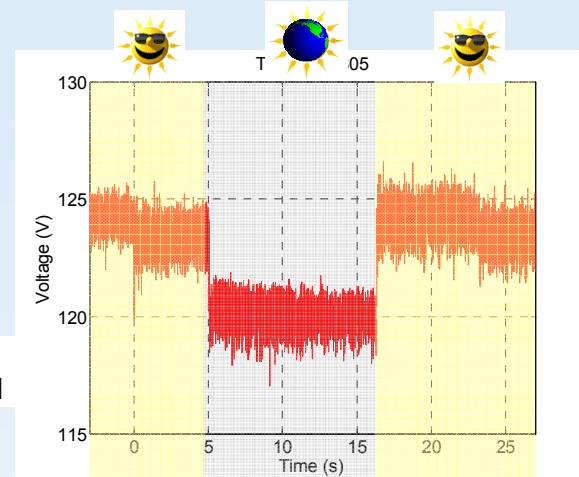


Mode	Current	DC Bus Voltage	Power Regulation Mode	Torque Command (N-m)	Load
Full Sun "Charge" 	$I_{s/a} = I_{load} + I_{charge}^*$ $I_{flywheel} = I_{charge}^*$	Regulated by solar array system	Test 1: Charge → Discharge → Charge	$T^* = 0$	1375, 585, 275, 125 W
Partial Sun "Charge Reduction" 	$I_{load} + I_{charge}^* > I_{s/a} > 0$ $I_{charge}^* > I_{flywheel}$	Regulated by flywheel system	Test 2: Charge → Discharge	$T^* = 0 \rightarrow 0.5 \rightarrow -0.5$	575 W
Eclipse "Discharge" 	$I_{load} = -I_{flywheel}$ $I_{flywheel} < 0$	Regulated by flywheel system	Test 3: Charge → Discharge	$T^* = 0 \rightarrow 0.7 \rightarrow -0.7$	40 W

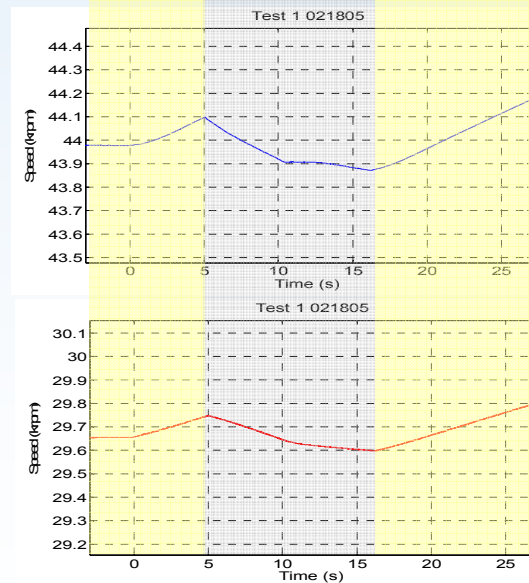
Bus Regulation DC Currents



DC Bus Voltage

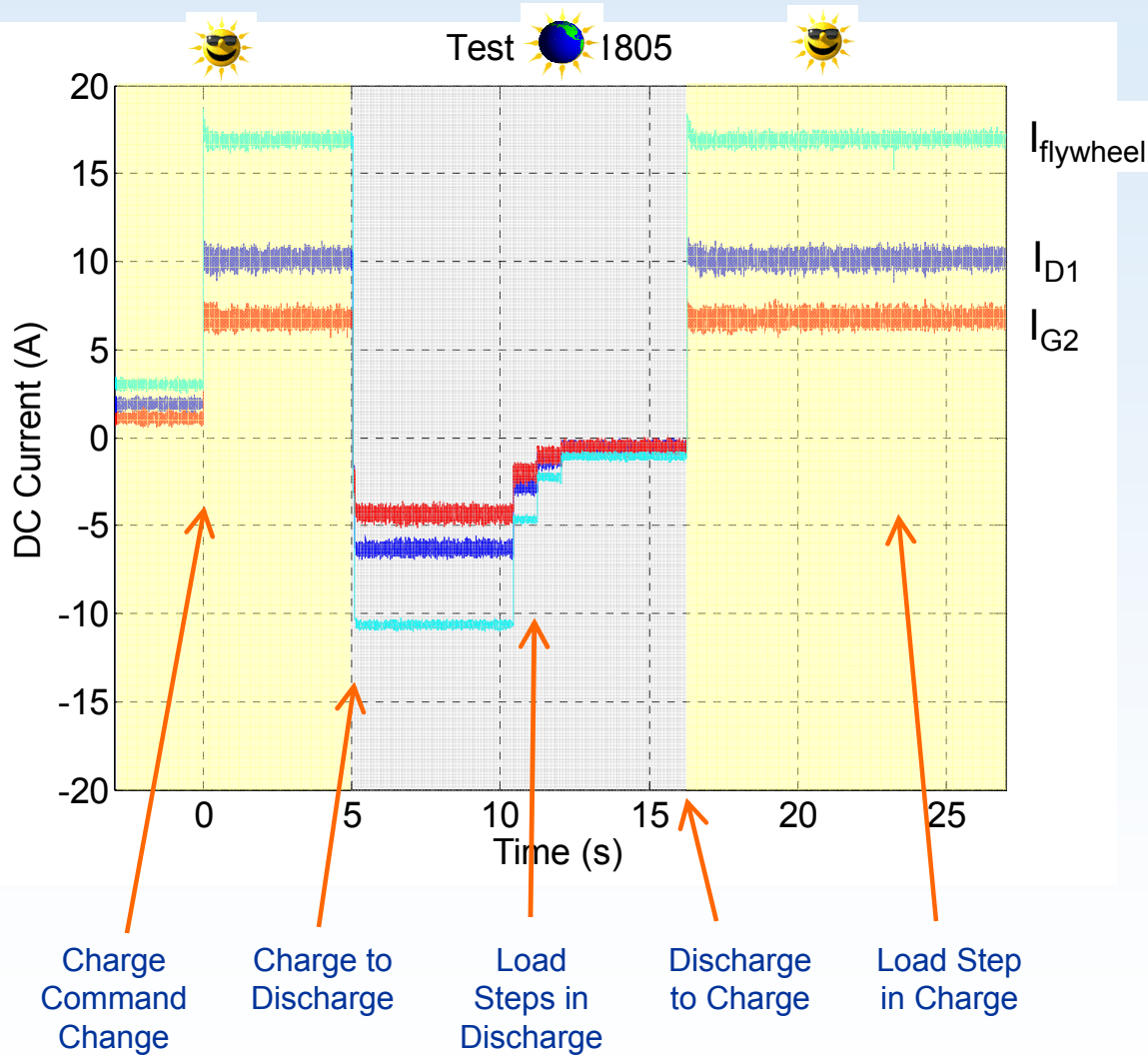


Rotor Speeds

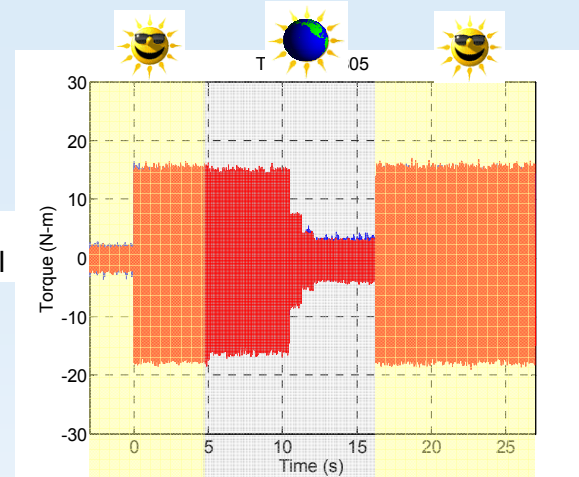


What do the motor currents look like?

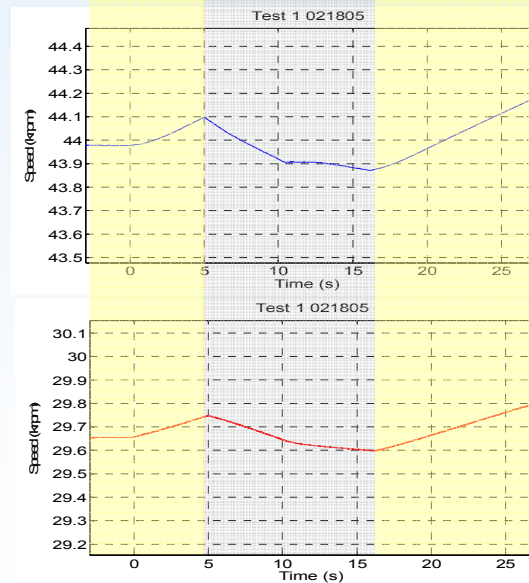
DC Currents



Motor AC Current (I_q)

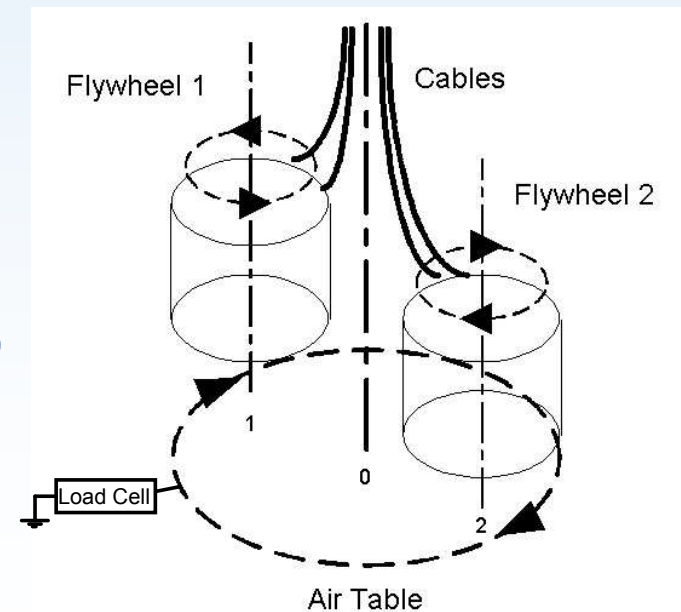


Rotor Speeds





Attitude Control and Bus Regulation

- Single axis system
- Objective: control axial torque and DC power simultaneously.
 - DC power command results from DC bus regulation algorithm
- Commanded table torque and DC power translated to two motor torque commands.






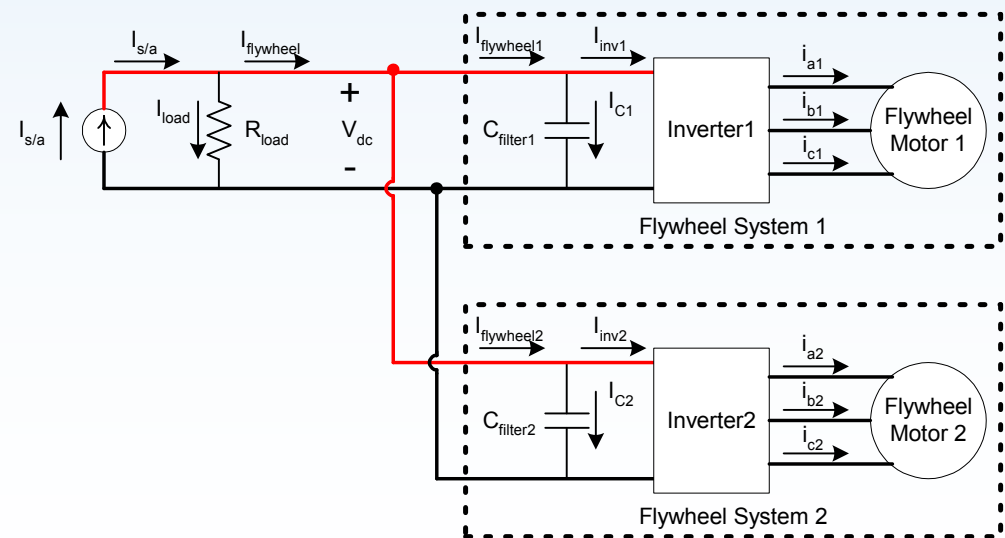
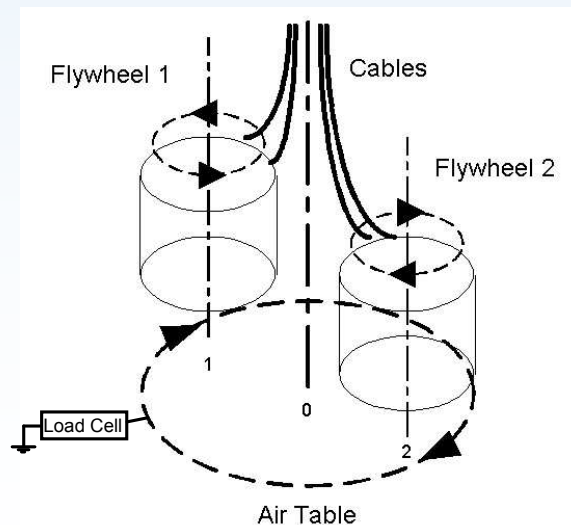
Integrated Power and Attitude Control

Open Loop Torque Control

Power Regulation Mode	Torque Command (N-m) 	Load 
Test 1: Charge → Discharge → Charge	$T^* = 0$	1375, 585, 275, 125 W
Test 2: Charge → Discharge	$T^* = 0 \rightarrow 0.5 \rightarrow -0.5$	575 W
Test 3: Charge → Discharge	$T^* = 0 \rightarrow 0.7 \rightarrow -0.7$	40 W

Closed Loop Bus Regulation

Mode	Current	DC Bus Voltage
Full Sun "Charge" 	$I_{s/a} = I_{load} + I_{charge}^*$ $I_{flywheel} = I_{charge}^*$	Regulated by solar array system
Partial Sun "Charge Reduction" 	$I_{load} + I_{charge}^* > I_{s/a} > 0$ $I_{charge}^* > I_{flywheel}$	Regulated by flywheel system
Eclipse "Discharge" 	$I_{load} = -I_{flywheel}$ $I_{flywheel} < 0$	Regulated by flywheel system

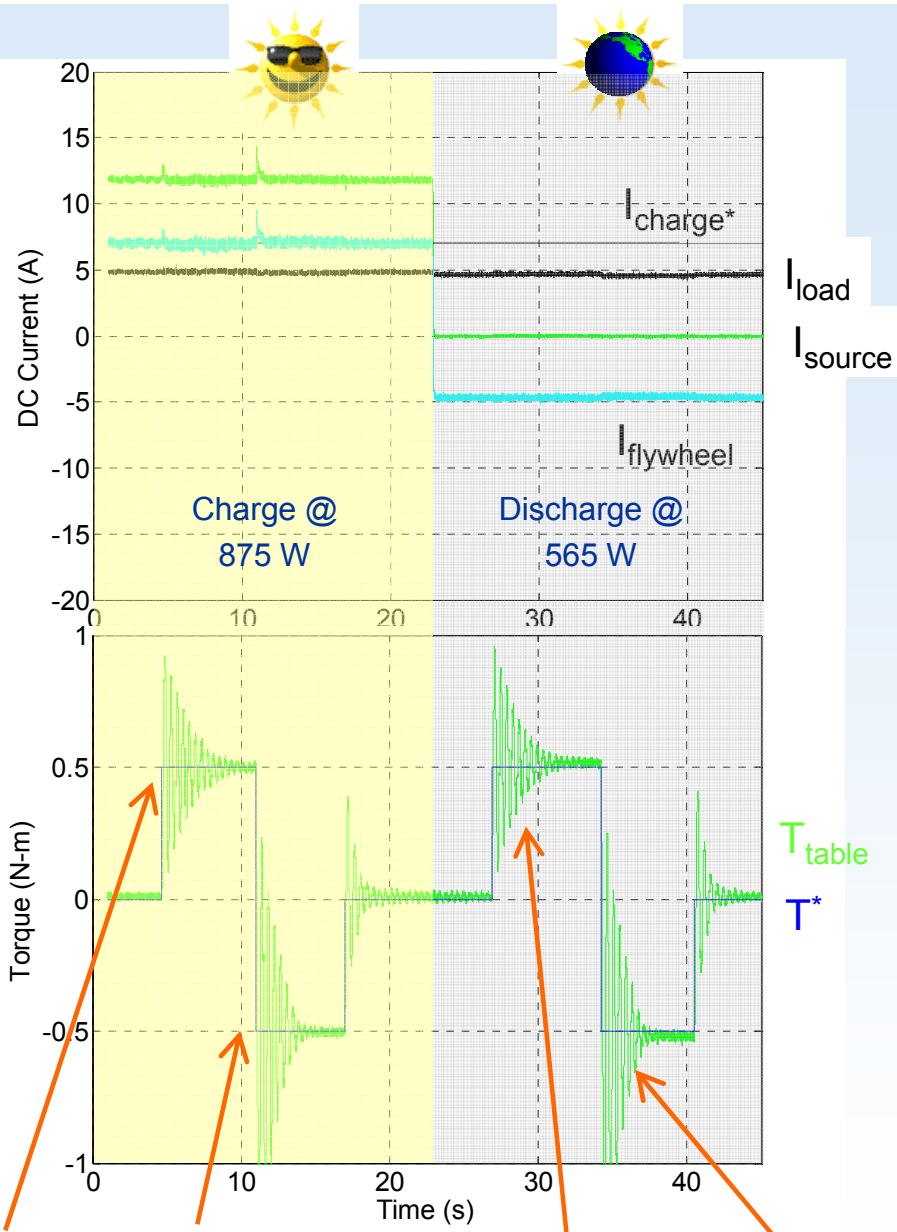




DC Current



Table Torque



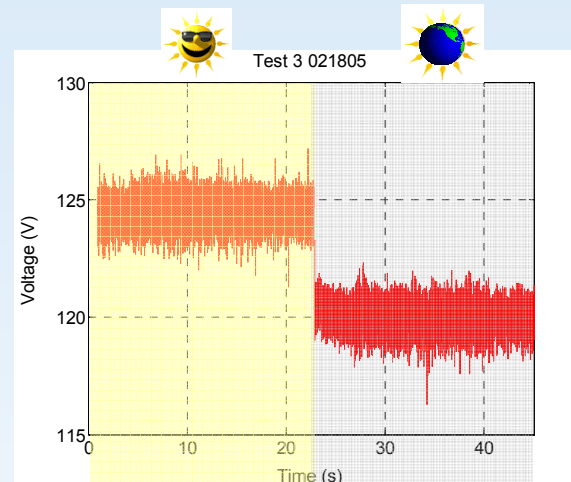
Positive & Negative
Torque Steps in Charge

Positive & Negative
Torque Steps in Discharge

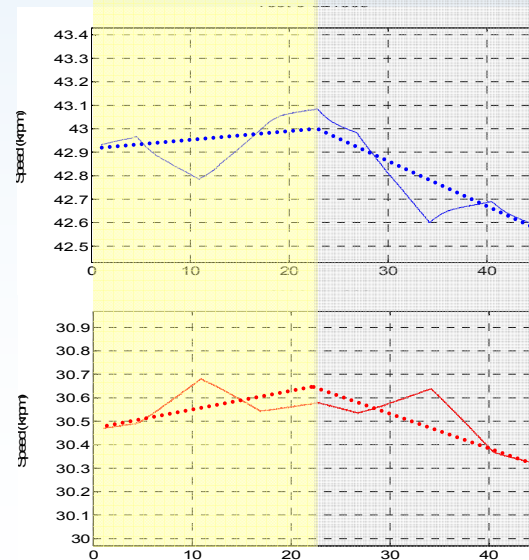
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Torque & Power

DC Bus Voltage



Rotor Speeds



at Lewis Field

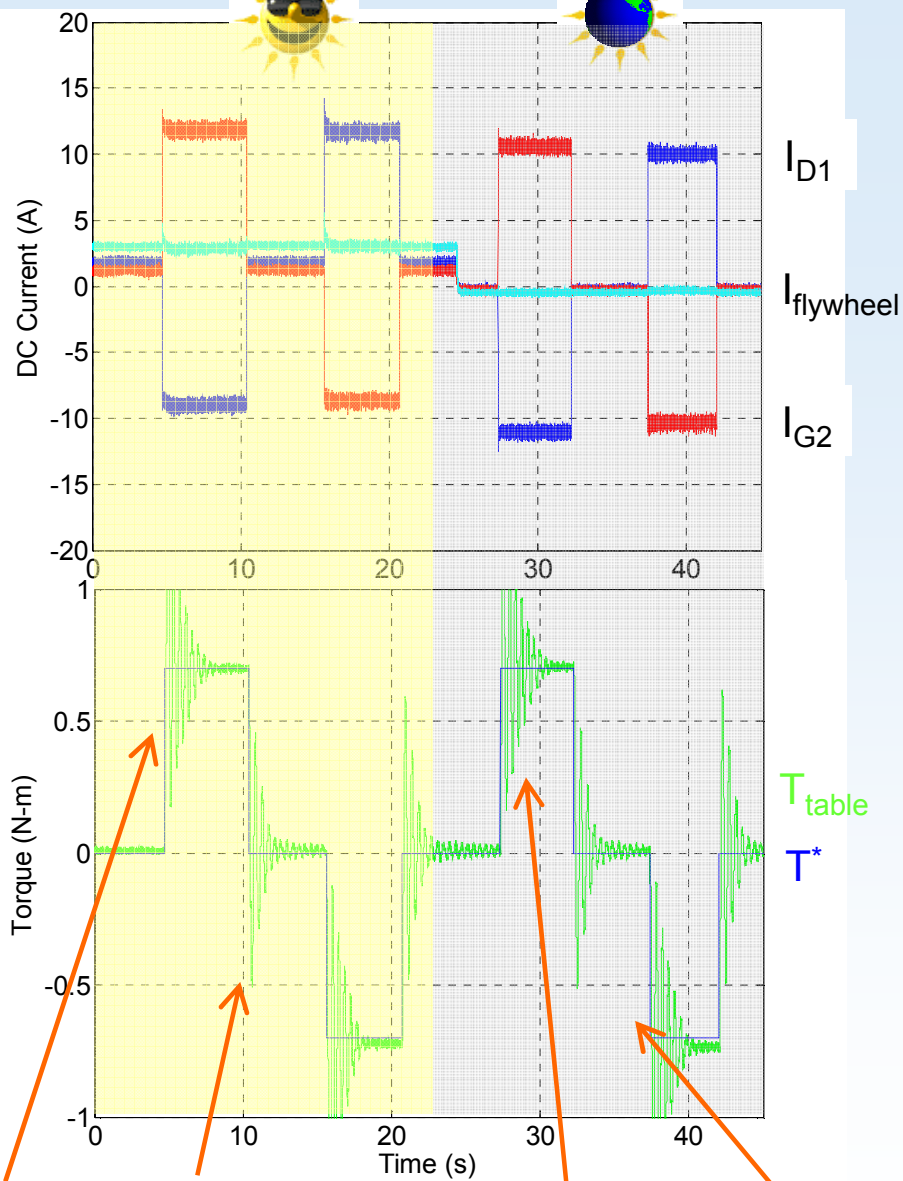




DC Current



Table Torque



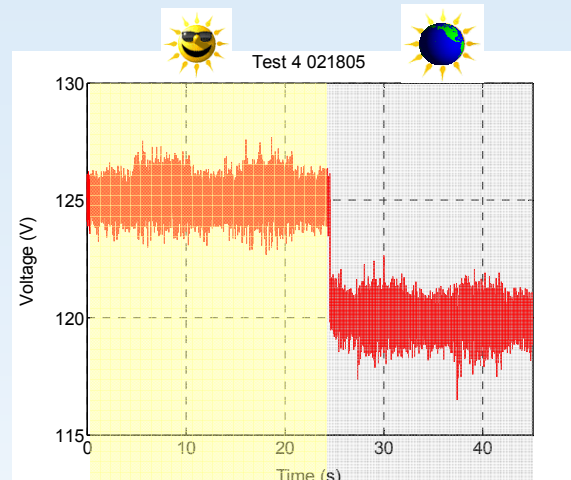
Positive & Negative
Torque Steps in Charge

Positive & Negative
Torque Steps in Discharge

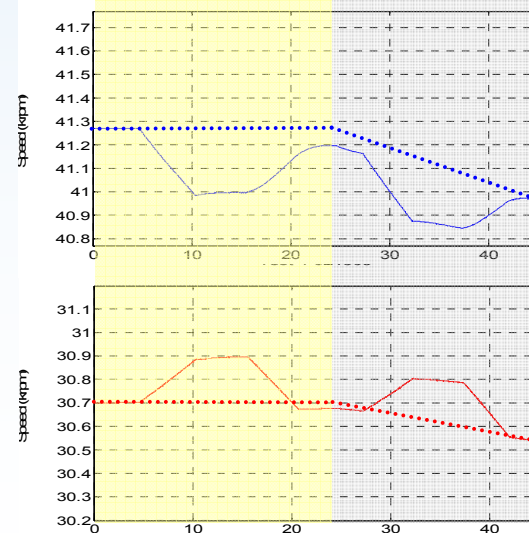
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Torque

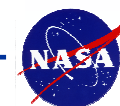
DC Bus Voltage



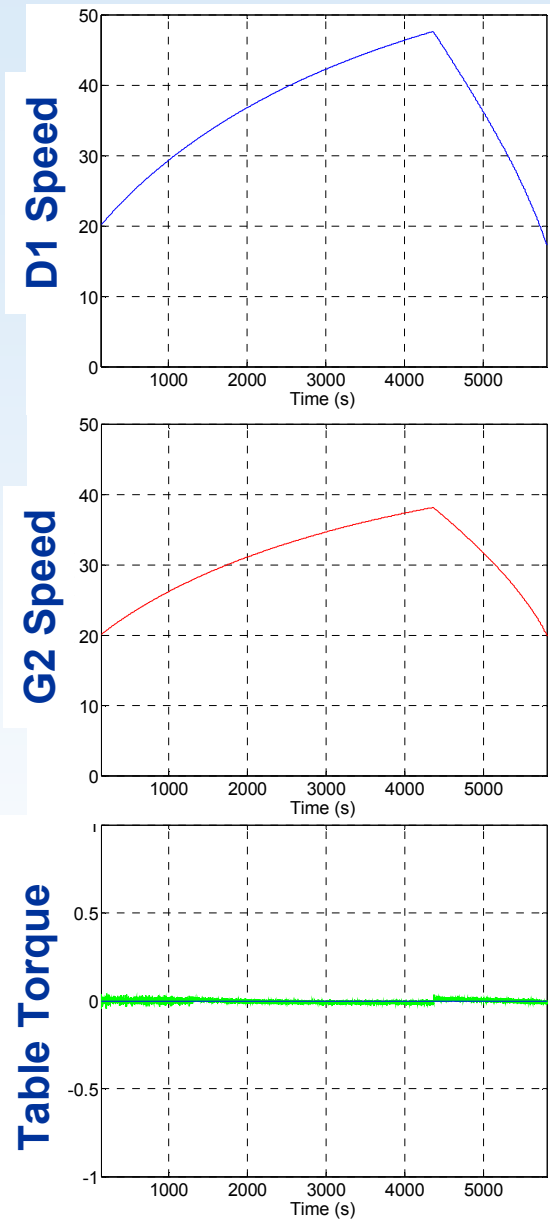
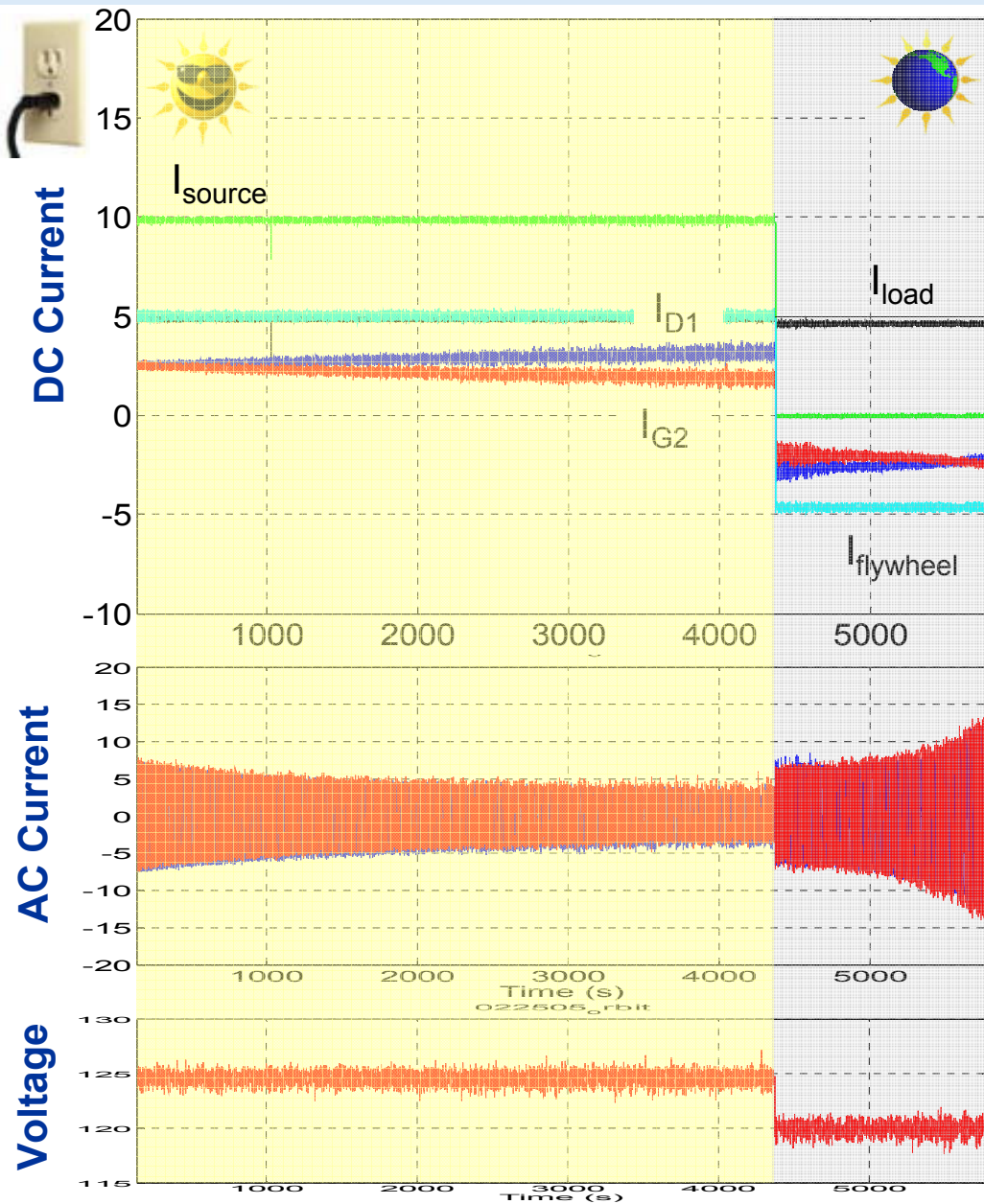
Rotor Speeds



at Lewis Field

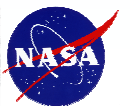


95 Minute Orbit Simulation (Initial Results)



Future Work

- The G3 flywheel module must be completed to demonstrate the specific energy capability of a flywheel system
- A high efficiency compact set of avionics must be built for use in conjunction with G2 or G3 to demonstrate the system level efficiency number
- Control algorithms must be migrated from dSpace to FPGA hardware
- A flight demonstration opportunity must be secured



Conclusions

- NASA GRC has demonstrated single axis combined attitude control and energy storage (IPAC) using two flywheels at full power and speed.
 - Single axis torque and DC power can be independently controlled and regulated.
 - DC bus voltage is accurately regulated by flywheels in discharge mode during load and/or torque steps.
 - DC bus power and table torque are independently controlled.
- Initial Orbit Simulations have been completed

